# The Wake Vortex Prediction and Monitoring System WSVBS Part II: Performance and ATC Integration at Frankfurt Airport

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**The performance and the ATC test integration of DLR's wake vortex advisory system, WSVBS, for the dependent parallel runways 25L and 25R at Frankfurt Airport are described. WSVBS has components to forecast and monitor the local weather and to predict and monitor wake transport and decay along the glide paths. Integration with the DLR's arrival manager AMAN has also been demonstrated. Every 10 minutes the WSVBS delivers minimum safe aircraft separation times for the next hour, which are translated into operational modes for runways 25L/R aiming at tactically improving capacity to reduce delays. During a performance test described herein the system was stable and the predicted minimum separation times were confirmed by measurements. Capacity-improving wake-vortex separation concepts of operation could have been used in 75% of the time and continuously applied for at least several tens of minutes.**

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Received March 23, 2009; accepted August 25, 2009.

Air Traffic Control Quarterly, Vol. 17(4) 323–346 (2009)
 CCC 1064-3818/95/030163-20

**From fast-time simulations the (strategic) capacity gain for Frankfurt was estimated to be 3%, taking into account the real traffic mix and operational constraints.**

## INTRODUCTION

Since aircraft trailing vortices may pose a potential risk to following aircraft, vortex separation standards between consecutive aircraft had been introduced as early as in the 1970s. These empirically motivated separation standards still apply, are often overly conservative, and limit the capacity of congested airports in a rapidly growing aeronautical environment. Capacity limitations are especially drastic and unacceptable at airports like in Frankfurt (Germany) with two closely spaced parallel runways (CSPR) where the possible transport of wakes from one runway to the adjacent one by crosswinds impedes an independent use of both runways.

To increase airport capacity for landing aircraft, DLR has developed a wake vortex advisory system named WSVBS, German for Wake Vortex Prediction and Monitoring System [Gerz et al., 2005]. The WSVBS is intended to dynamically adjust aircraft wake vortex separations dependent on weather conditions and the resulting wake vortex behaviour without compromising safety. The system is particularly designed for the closely spaced parallel runway system of Frankfurt Airport (Figure 1) but can be adapted to any other airport. It predicts wake vortex transport and decay and determines the resulting wake vortex safety areas along the glide slope, from the final approach fix to the threshold. The design of the WSVBS is described in Part I [Holzäpfel et al., 2009b]. In this paper we describe its performance during a test campaign at Frankfurt Airport and indicate possible gains in capacity, if the WSVBS were installed there and used by air traffic control (ATC) authorities.

## INSTALLATION AT FRANKFURT AIRPORT

The WSVBS with its components (*tools*)

- weather forecast (*NOWVIV*),
- wake vortex predictor (*P2P*),
- safety area predictor (*SHAPe*),
- weather profiler (*SODAR/RASS/USA*), and
- wake detector (*LIDAR*)

was evaluated at Frankfurt Airport in the period of December 2006 until February 2007. The system used forecast and measured meteorological parameters along the glide path to predict temporal wake vortex separations of aircraft landing on the parallel runway


**Figure 1.** Frankfurt Airport with the two parallel runways 25L and 25R, spaced by 518 m (1727 ft).

system 25L/R. The system also translated the required separation between two aircraft into approach procedures that could have been employed by air traffic control ATC. At the same time, the actual transport of the wake vortices was monitored by the wake detector component (LIDAR) in 3 different control gates. All components of the WSVBS are described in detail in [Holzäpfel et al., 2009b]. Here we note some specific features of the set-up at Frankfurt Airport.

Figure 2 sketches the instrumentation layout at Frankfurt Airport. It depicts runways 25L and 25R with the locations of the employed sensors and the local operation centre (LOC) which is located in the observer house of the German Meteorological Service (DWD). Close to the LOC, midway between the glide paths, a SODAR with a RASS extension provides 10-minute averages of vertical profiles of the three wind components, vertical fluctuation velocity, and virtual temperature with a vertical resolution of 20 m up to 300 m AGL. The SODAR/RASS system is complemented by an ultrasonic anemometer (USA) mounted on a 10 m mast which measured wind and temperature with a frequency of 20 Hz. Eddy dissipation rate (EDR) profiles are derived from the vertical fluctuation velocity and the vertical wind gradient employing a simplified budget equation [Frech, 2007]. A spectral analysis of the longitudinal wind velocity measured by the

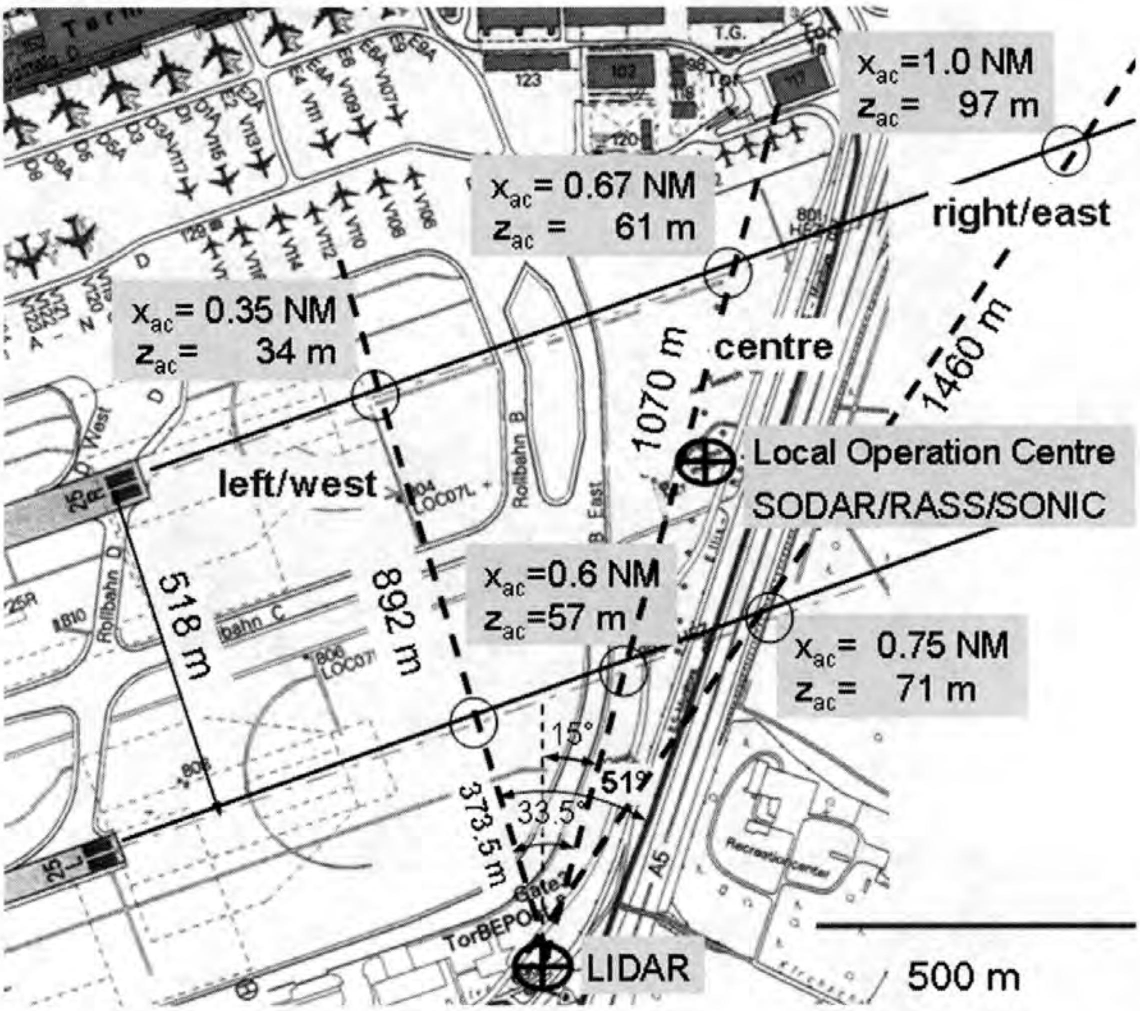



**Figure 2.** The instrumentation layout at Frankfurt Airport; $x_{ac}$, $z_{ac}$ denote the distance to touch-down zone and the height of landing aircraft in the three vertical scan planes of the LIDAR (dashed lines); LOC and the meteorological profiler were situated between both extended runway centrelines. Map reprinted by courtesy of Fraport AG.

sonic anemometer is used to estimate EDR by fitting the -5/3 slope in the inertial sub-range of the velocity frequency spectrum. Due to the position of the SODAR/RASS/USA between the extended centrelines of both runways these data are considered representative of the area where aircraft and vortices are in ground proximity. In the LOC, a Linux-PC is installed which is connected via ethernet to the SODAR/RASS/USA system and via UMTS (Universal Mobile Telecommunications System) to the computers at DLR and to the LIDAR container. This PC serves as a front-end for the weather and wake forecasts and observations.

The weather forecast model NOWVIV [Gerz et al., 2005; Frech et al., 2007; Frech and Holzäpfel, 2008] ran twice a day on a massively parallel Linux cluster at University Stuttgart. It predicted the meteorological conditions for the Frankfurt Airport Terminal Area. The forecast output was sent via UMTS to the Linux-PC in the Local Operation Centre (LOC) to be used by the real-time wake predictor, P2P (Figure 3).

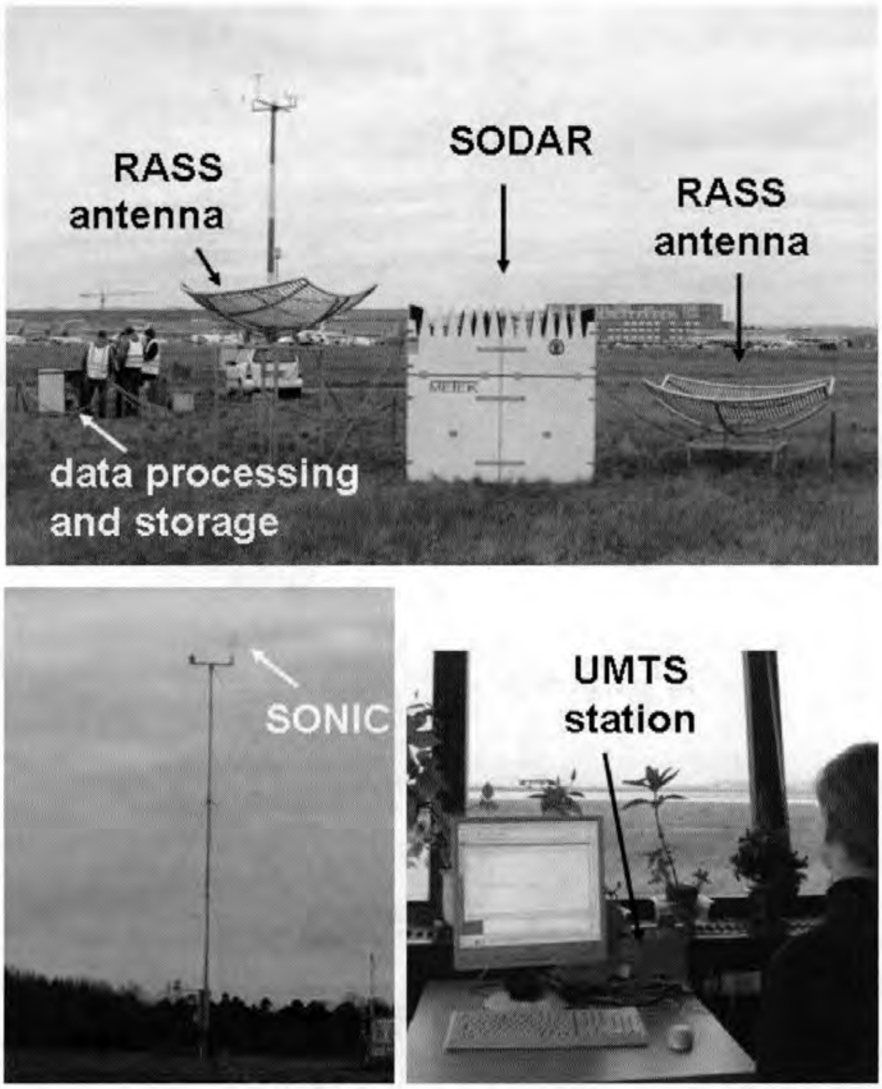
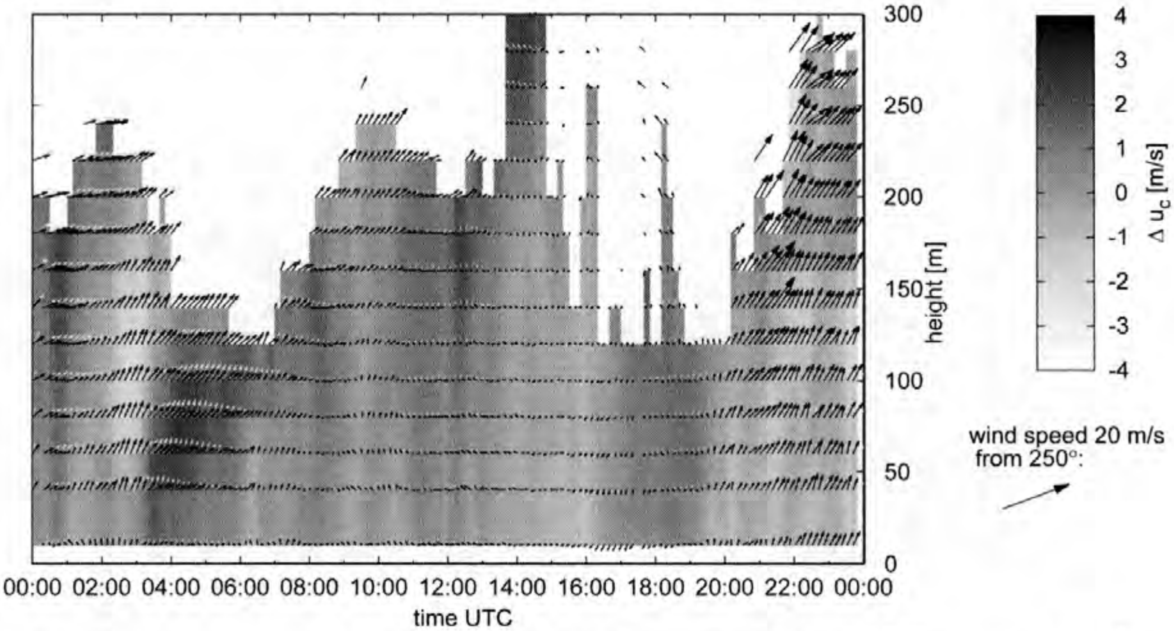



**Figure 3.** Meteorological instruments at Frankfurt Airport. Top & lower left: SODAR/RASS and USA by Fa. Metek; lower right: the LOC with Linux-PC & UMTS station in the DWD observer house.

Figure 4 shows two examples of diurnal variations of horizontal wind profiles, a weak wind condition on 15$^{th}$ of January and a stronger wind case on the following day. The height range covered by the SODAR/RASS measurements depends on the backscatter properties and ambient noise level in the boundary layer which vary during the day. The NOWVIV forecasts are only plotted in the range where observations were available. Also indicated are the differences between observed and predicted cross-wind $u_c$. On the calm day the deviation between observation and prediction was about $\pm 1.5$ m/s on average but considerably larger in the early morning hours between 2 and 5 UTC. This was due to a south-westerly low level jet which developed and vanished earlier than anticipated by the NOWVIV forecast. The temporal deviations produced the dark and light grey coloured $u_c$-deviation dipole shown in Figure 4. Hence, the phenomenon – a low level jet – was predicted but with a delay of about 2 hours. A similar phenomenon was observed on the next morning but, in this



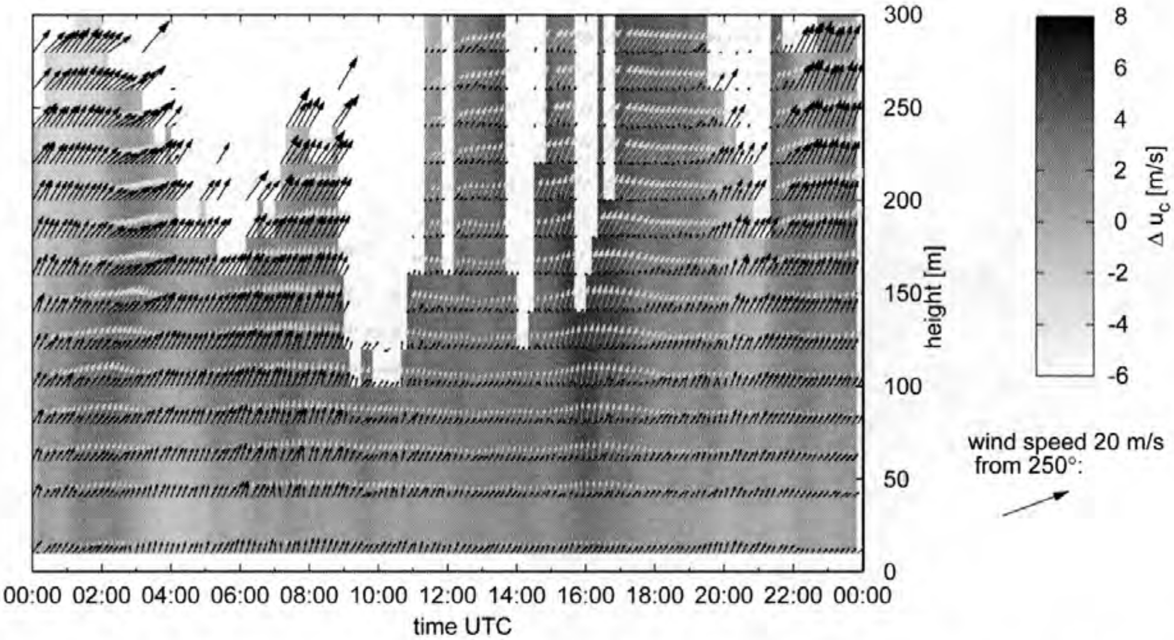




**Figure 4.** Diurnal variations of the wind velocity profile measured by SODAR/RASS (black arrows) and predicted by NOWVIV (grey arrows) on 15.01.07 (top) and 16.01.07 (bottom). Deviations in cross-wind $u_c$ between observation and prediction are coded in grey-scale. White areas indicate no measurements.

case, the jet developed later than predicted. The generally higher winds on the $16^{th}$ of January also indicate that the weather was dominated by advection processes (large scale weather patterns). Under these conditions the initial and boundary conditions for NOWVIV have a larger impact on the forecast quality than on the $15^{th}$ where the weather was driven by local orographic and land-use features.

The real-time probabilistic two-phase wake vortex decay and transport model P2P [Holzäpfel, 2003; Holzäpfel and Robins, 2004; Holzäpfel, 2006; Holzäpfel and Steen, 2007; Frech and Holzäpfel, 2008; Holzäpfel et al., 2009a] received the measured and forecast meteorological profiles as inputs. It computed envelopes of probable decay and location of the wake vortices of aircraft from the HEAVY (H) aircraft category in thirteen gates along the glide path to runways 25L/R. The Linux-PC in the LOC performed the P2P wake model calculations. The Simplified Hazard Area Prediction (SHAPe) model [Hahn et al., 2004, Schwarz and Hahn, 2005, 2006, Holzäpfel et al., 2009b] then computed safety zones around the area of the probable vortex locations.

DLR's 2 μm pulsed Doppler LIDAR was used to monitor the correctness of the predictions of the WSVBS at Frankfurt Airport. It operated in vertical scan-plane mode with elevations between 0° to 6° to detect and track the vortices alternately in the three lowest and most critical planes (Figure 2). The line-of-sight (LOS) velocity in a scanned plane is immediately visible in the so-called "quick-look". These quick-look files were transmitted via UMTS to the LOC computer and were also accessible via internet. Figure 5 shows a quick-look result from 16 January 2007 at 04:17 UTC in the "centre" vertical scan plane.

In that hour, most heavy aircraft landed on runway 25R (the northern runway). The Figure 5 quick-look results show the LOS wind component. Patterns of wind shear and of a wake vortex pair can be distinguished. The quick-look also indicates roughly the position of the two flight corridors for landing aircraft in the scan plane. Thus, it is possible to check if the predicted minimum separation times are correct: the vortices visible in the LIDAR quick-look should not reside within the flight corridors when the WSVBS predicts that it is safe for the next aircraft to enter the control gate. The quick-

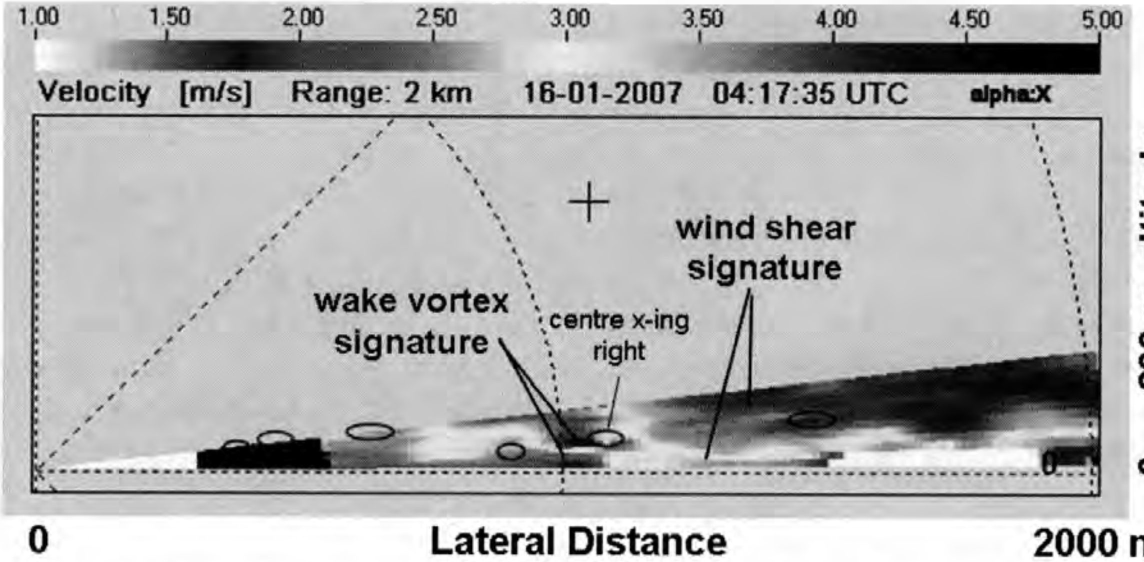



**Figure 5.** LOS velocity as measured by LIDAR (quick-look after one scan, positive values indicate velocities away from the instrument) with signatures of wind shear and a wake vortex pair. The crossings of the laser beam with the glide path gates in Figure 2 are indicated by small ellipses; "centre x-ing right" identifies the approximate intersection of the beam in scan plane "centre" with runway 25R at 1070 m distance.

look, however, only allows for a rough estimate of the vortex location. After signal and image (post-) processing, the spatial resolution of the LOS velocity is 3 m and the wake vortex position (and strength) can be deduced with high accuracy.

## INTEGRATION INTO ATC PROCEDURES

### The Concepts of Operation

The German Air Safety Provider, DFS, has established four modes, or concepts of operation, for aircraft separation to be applied for the dependent parallel runway system at Frankfurt Airport under instrumented meteorological conditions (IMC) [Gurke and Lafferton, 1997], see Figure 6:

- "ICAO" – standard procedure under IMC with 4 nmi for a HH aircraft pair and 5 nmi for a HM pair across both runways;
- "Staggered" (STG) – procedure where both runways can be used independently from each other but obeying the radar (minimum) separation of 2.5 nmi;
- "Modified Staggered Left" (MSL) – aircraft on right (windward) runway keep 2.5 nmi separated from aircraft of left (lee) runway;
- "Modified Staggered Right" (MSR) – aircraft on left (windward) runway keep 2.5 nmi separated from aircraft of right (lee) runway.

Note that in all modes, all aircraft in-trail (approaching the same runway) remain separated according to ICAO standards. The modes STG, MSL, MSR can only be applied in favorable weather conditions (especially favorable cross-wind) and require the use of a wake vortex advisory system as DLR's WSVBS or DFS' wake vortex warning system, WVWS [Gurke and Lafferton, 1997]. These modes are not used operationally today.

Table 1 translates the operationally applied separation distances for HH, HM and radar separation into separation times which must be followed in each concept of operation and for each runway combination. For 5 and 4 nmi separation we applied an approach speed of 74 m/s (144 kn) to all aircraft, following the conservative parameter setting in DLR's Arrival Manager, AMAN. For the minimum (radar) separation we took a conservative 70 s (instead of 62.5 s).

### The Prediction Cycle

The installation of the WSVBS at Frankfurt Airport was accomplished on the 19$^{th}$ of December, 2006. It then delivered data for 66 days until the 28$^{th}$ of February, 2007. The wake predictive chain started with the forecast of the local weather twice a day at 0 and 12 UTC. The SODAR/RASS/USA operated continuously 24 hours a

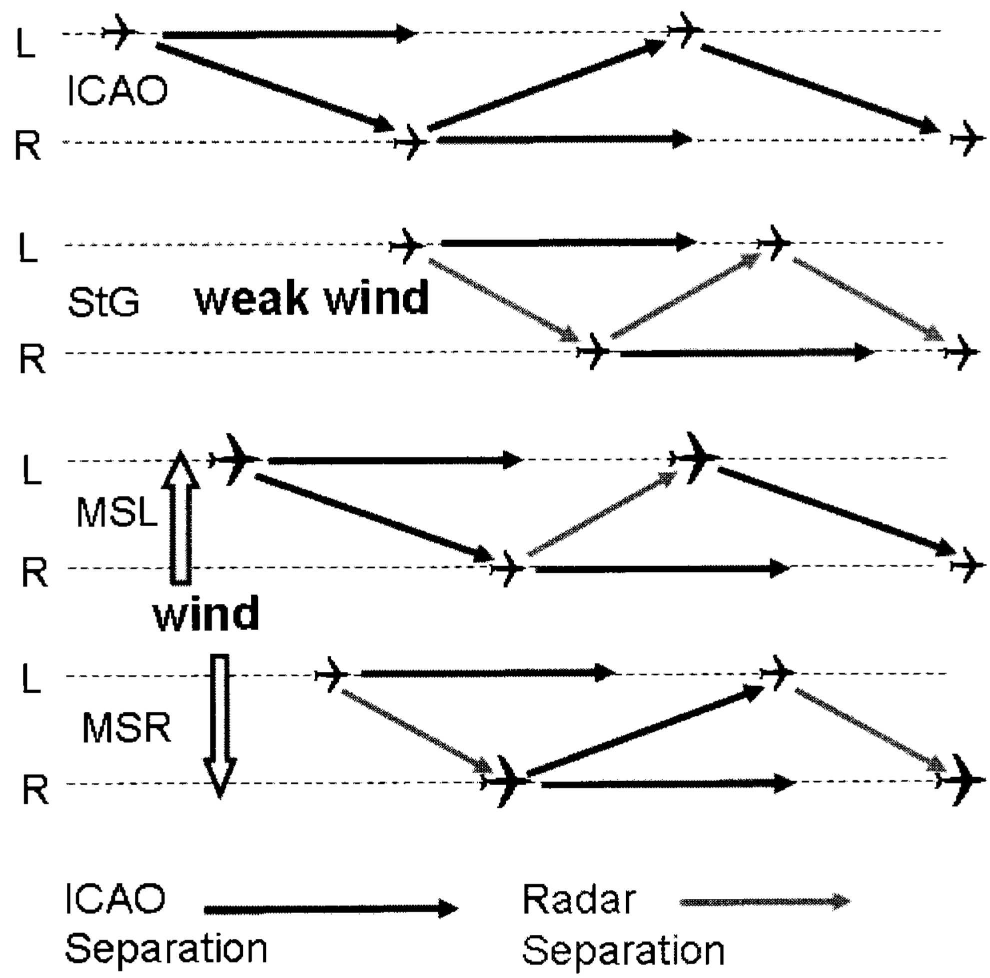



**Figure 6.** The concepts of operation under IMC for the dependent parallel runway system at Frankfurt Airport.

day and delivered measured weather profiles every 10 min. With these weather data, the areas of possible vortex locations and the surrounding safety areas were computed by P2P and SHAPe. The forecast of minimum safe wake separations was made every 10 min for both runways at all 13 gates with a forecast horizon of 60 min.

**Table 1. Aircraft Separation Times for the Four DFS Concepts of Operation ICAO, STG, MSL, MSR and the Four Runway Combinations of Leader and Follower Aircraft (e.g., RL = leader on 25R, follower on 25L runway)**

| *ICAO* | H-H | H-M | *STG* | H-H | H-M |
|---|---|---|---|---|---|
| LL | 100 s | 125 s | LL | 100 s | 125 s |
| LR | 100 s | 125 s | LR | 70 s | 70 s |
| RL | 100 s | 125 s | RL | 70 s | 70 s |
| RR | 100 s | 125 s | RR | 100 s | 125 s |
| ***MSR*** | **H-H** | **H-M** | ***MSL*** | **H-H** | **H-M** |
| LL | 100 s | 125 s | LL | 100 s | 125 s |
| LR | 100 s | 125 s | LR | 70 s | 70 s |
| RL | 70 s | 70 s | RL | 100 s | 125 s |
| RR | 100 s | 125 s | RR | 100 s | 125 s |

After consultation with controllers, it was assumed that they require at least 45 min lookahead time to utilize the WSVBS system. The *minimum separation time (MST)* between two aircraft landing on the same or the adjacent parallel runway is determined by the maximum time that the predicted wake safety area overlaps the approach corridor. The time is computed in all gates for the respective aircraft weight class combinations.

Based on the MST, landing procedures were eventually recommended and displayed on the PC in the Local Operation Centre as shown in Figure 7 and Figure 8; they were also accessible remotely via the Internet. Figure 7 is updated every ten minutes and adjusted for the progression of time each minute. The figure shows that for most of the forecast time the operational procedure MSL can be used with a short period where the (northerly) wind is so weak that the runways can be used independently (STG). After 50 minutes the WSVBS system anticipates a change that requires a return to the standard separations (ICAO).

Figure 8 displays the full MST information as it is available in the WSVBS. In addition to the four procedures which were defined by DFS, such a display also allows surveying possible reduced separations for aircraft flying in-trail and it further distinguishes HH and HM aircraft pairs. The sketched example indicates that the DFS procedure MSL can be used (no wake-vortex separation required for runway combination 25L25R but full ICAO separation for 25R25L), and, in addition, aircraft which follow each other on the same runway (in-trail) can be radar-separated. The meteorological reason for that case is a strong northerly crosswind that clears both runways quickly from vortices of the leading aircraft.

## The Human-machine Interfaces

The proposed operational procedures for up to one hour were also displayed on simulated controller screens for the real-time

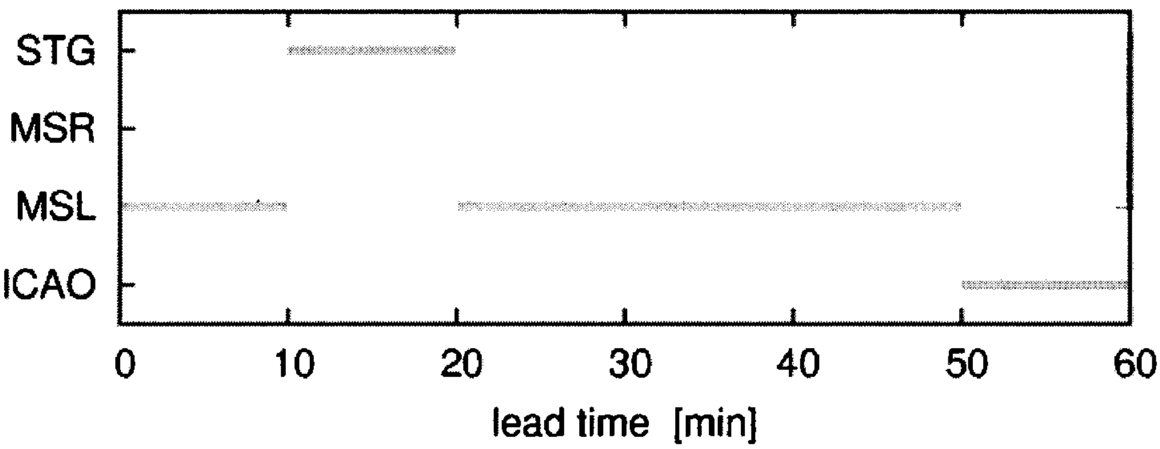



**Figure 7.** Indicated use of DFS approach procedures within the next hour.

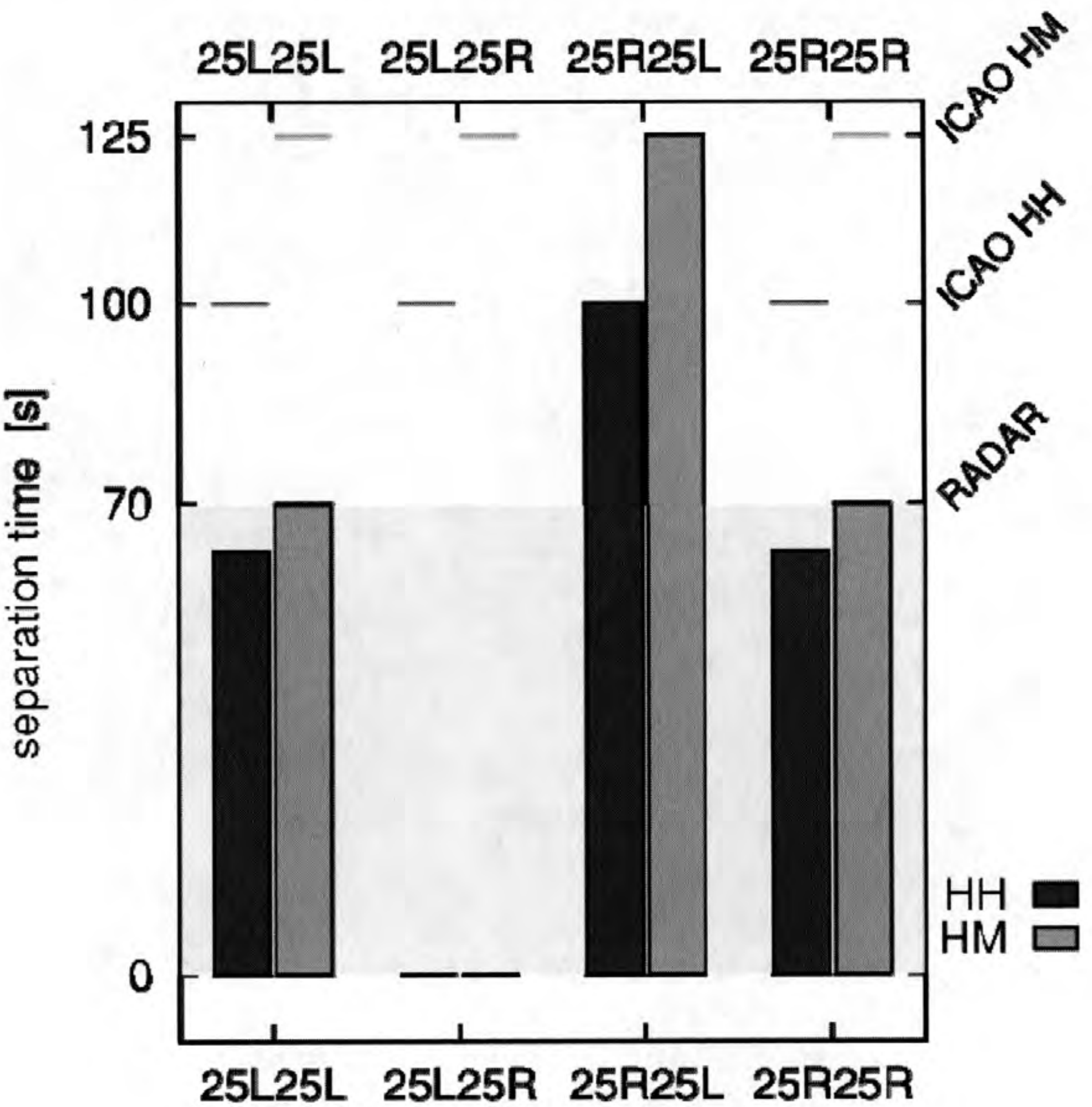



**Figure 8.** Display of full MST information and derived arrival procedures for Frankfurt Airport on 2007-Jan-25 at 15:10 UTC.

evaluations. The display layout was developed in consultation with controllers and deemed acceptable for operational use. Figure 9 shows a controller planning screen with two bars along the dynamic time scale up to 37 min indicating mode MSL for the period 07:06 until 07:29 and mode STG afterwards. Upon request from controllers the forecast wind direction and speed at heights FL 70 and 4000 feet and at ground level were also displayed. Another situation is depicted on a controller radar screen shown in Figure 10, where the parallel runways can be seen by two tiny lines (see arrow). The final approach path of the northern runway is indicated by the time ladder. The thick bright lines parallel to it have a 12 min time horizon and appear when aircraft may be separated by 2.5 nmi. Hence, the situation displayed allows mode STG for the next 10 min, followed by mode MSL afterwards.

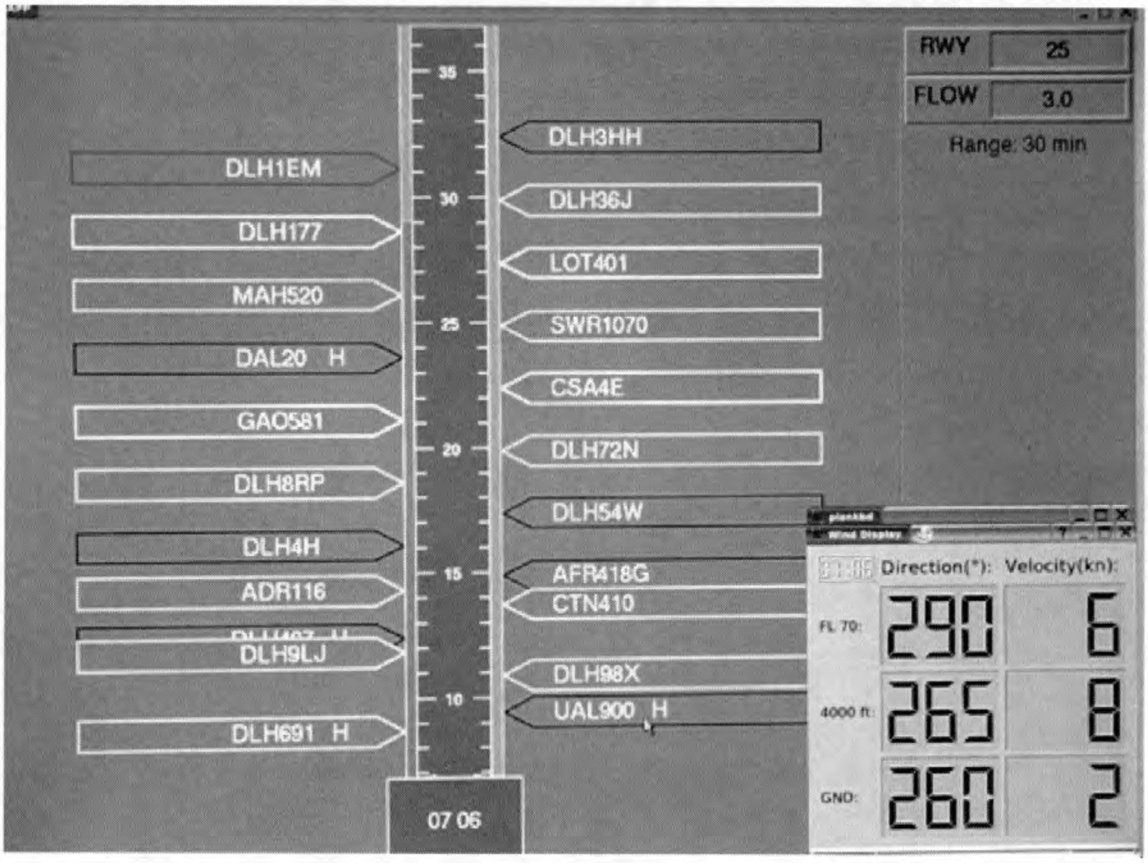



**Figure 9.** Controller's planning screen with dynamic time scale and wind information.

## PERFORMANCE AND IMPROVED CAPACITY

We performed real-time and fast-time simulations, employing the Air Traffic Management and Operations Simulator (ATMOS II) and the SIMMOD tool of DLR. During a one-week period real-time

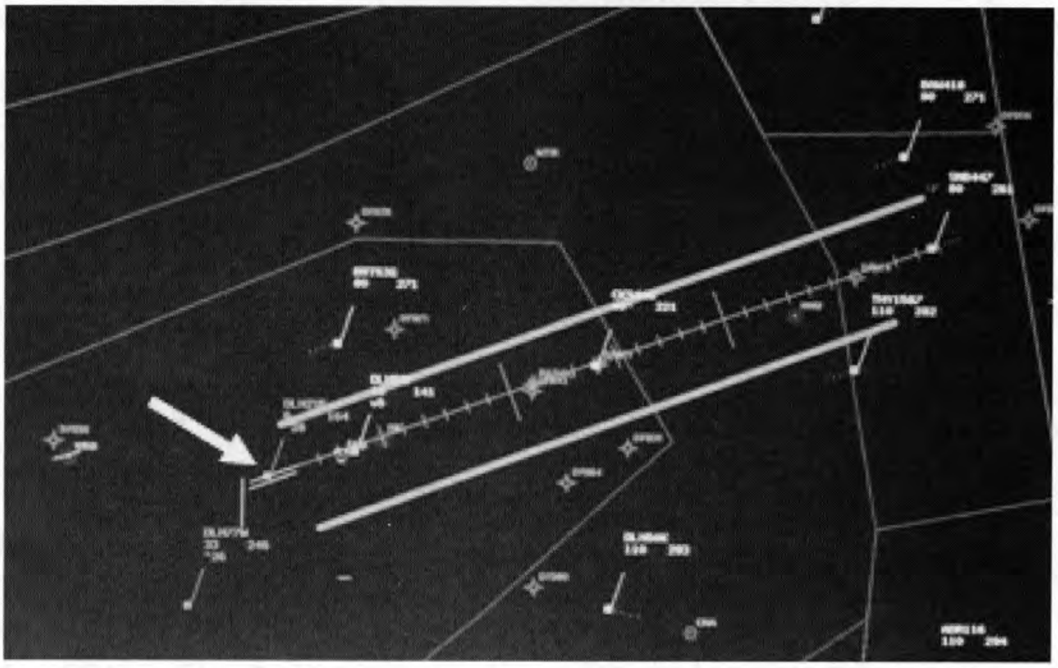


**Figure 10.** Controller's radar screen.

simulations were carried out at the simulator ATMOS II under the assistance of five air traffic controllers from the DFS. The investigation was aimed at determining the behaviour and efficiency of the WSVBS at a simulated real-time controller working position, and obtaining controller evaluations of the system.

By means of a questionnaire the controllers from DFS were interviewed with respect to aspects such as:

- acceptance of the simulation environment,
- acceptance of the WSVBS,
- procedural regulations and human interface,
- operational applicability.

The participating controllers generally found the WSVBS system and associated procedures acceptable. In particular, the system was judged not to interfere with their normal working procedures (Gerling et al., 2007).

We also performed fast-time simulations to obtain capacity figures for the different concepts of operation utilized by WSVBS under real world conditions. To establish a baseline, the simulations were initially performed using ICAO separations. The simulations were then matched with separations derived from WSVBS and re-run (Figure 11). The simulations included actual aircraft types and flight

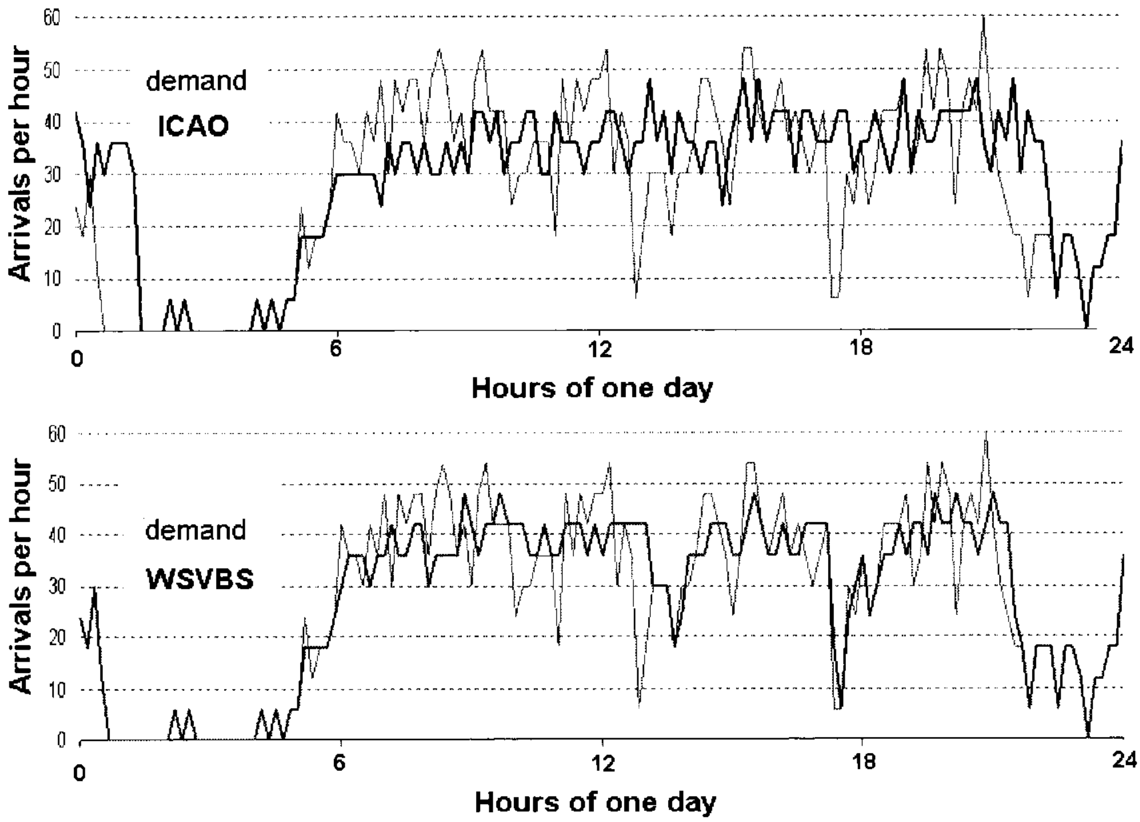



**Figure 11.** Traffic flow (arrivals per hour) during a day at Frankfurt Airport. Top: demand (grey) vs. ICAO standards (black); bottom: demand (grey) vs. WSVBS utilisation (black).

characteristics spanning a realistic distribution of wake vortex categories, demand peaks throughout the day, weather data, and the WSVBS proposed minimum wake vortex separations. The fast-time simulations covered a period of one month.

Figure 11 shows traffic demand and traffic flow for a "heavily loaded" day at Frankfurt with 721 arrivals. Using the WSVBS predictions, MSR separations could be used for 76.4% of the day, with intermittent use of ICAO separations in the morning hours. The peak demand exceeds capacity in both scenarios. However, the WSVBS flow closely follows the demand flow, whereas the ICAO flow is unable to cope with the demand and accumulates delayed flights which can only be resolved in the late evening hours.

Improved capacity at an airport offers a variety of options for future aircraft operations which range from an entirely tactical scenario (increase punctuality of flights while keeping number of landings constant) to an entirely strategic scenario (increase the average traffic flow at the expense of higher average delays). Figure 12 shows the theoretical capacity gain for the different concepts of operation. A SIMMOD model of the parallel runways at Frankfurt Airport was developed assuming a constant flow of arrivals and a traffic mix of 27, 67 and 6% of heavy, medium and light aircraft, respectively. For each average number of arrivals per hour ten iterations of the SIMMOD model were executed with randomized computed flight paths. The figure reveals that 2 to 5 more aircraft can land per hour when changing from ICAO mode to MSL/R or STG mode, respectively, if an average delay of 4 minutes is accepted. Or, vice versa, the average

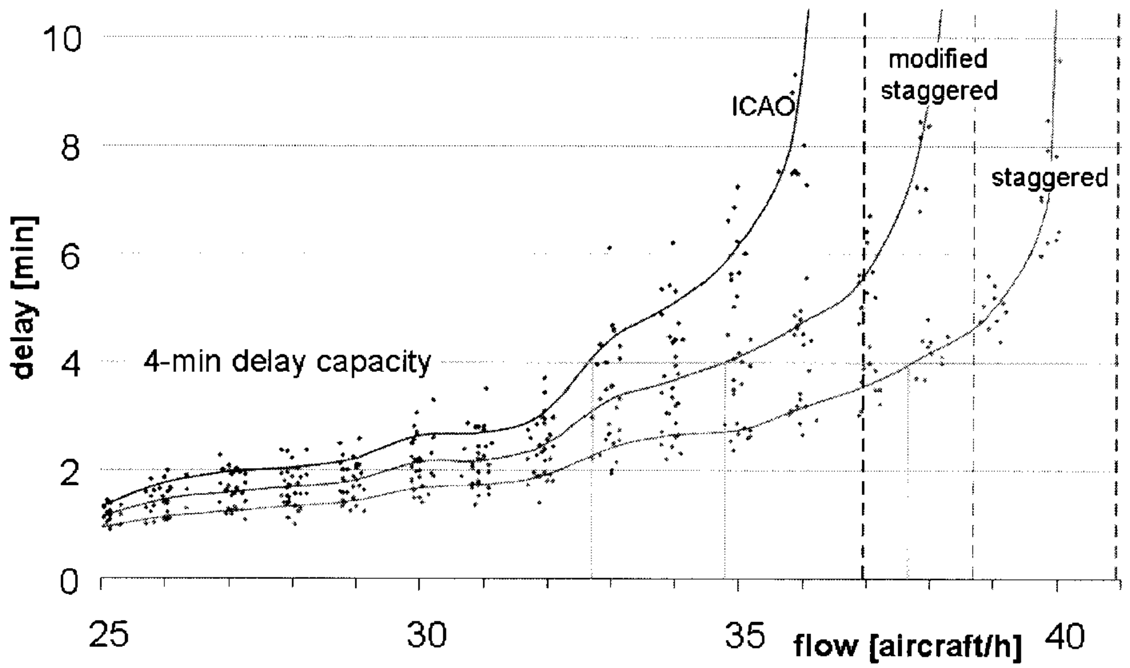



**Figure 12.** Average delay versus traffic flow (for a mix of H/M/L aircraft of 27/67/6%) for the concepts of operation ICAO, MSL/R, and STG from fast-time simulations; the "4-min delay" capacity is indicated by thin vertical lines.

delay of 4 minutes (ICAO) would drop down to a bit more than 2 minutes (STG) when keeping the arrival rate at almost 33 aircraft per hour. The figure also points out that a further increase of capacity beyond 39 arrivals per hour for mode STG would rapidly increase delays, since the system runs into its saturation point. When taking into account the real traffic mix and operational constraints in the one month period simulated we received a net capacity gain of slightly larger than 3%.

Figure 13 summarizes the history of potential usage of DFS-developed operation modes as proposed by WSVBS during the 66 days evaluation at the Frankfurt airport. It is evident that in the majority of time the proposed modes could have been deployed to improve capacity or punctuality of landing aircraft. A closer look at five specific days indicates that each mode can be deployed throughout a significant fraction of time (see also Figure 14).

Table 2 lists the use of all operation modes as predicted by WSVBS during the 66 day evaluation for the fraction of time in which radar separation of 2.5 nmi (70 s) was suggested. Thus, the table also includes reduced in-trail separation and differentiates between HH and HM aircraft pairs (cf. Figure 8). From the meteorological conditions which prevailed during that winter period, heavy aircraft could have landed behind heavy aircraft in-trail on R or L runway in 2.6% of the time with an average MST of 60 s (but *de facto* separated by 70 s). In another example, 47.9% of the time a medium aircraft could have landed 2.5 nmi behind the preceding heavy aircraft landing on R.

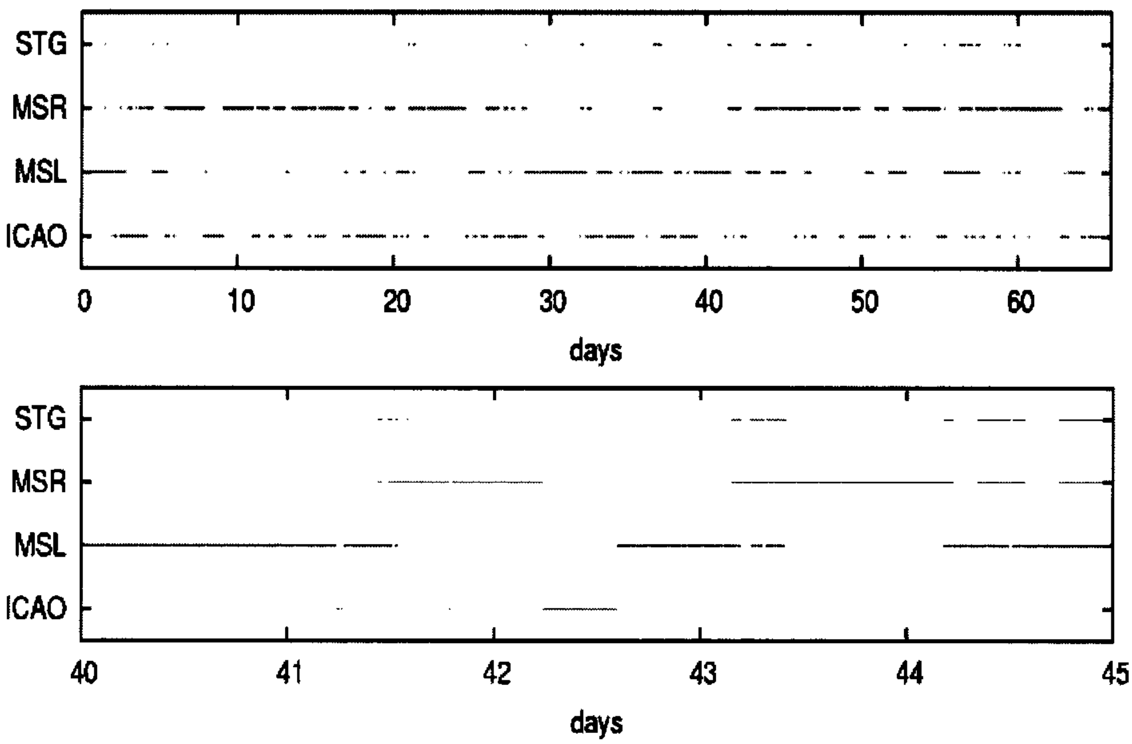



**Figure 13.** History of potential usage of the 4 DFS operation modes during the 66 days of the campaign at Frankfurt. Top: full period; bottom: zoom on five days.

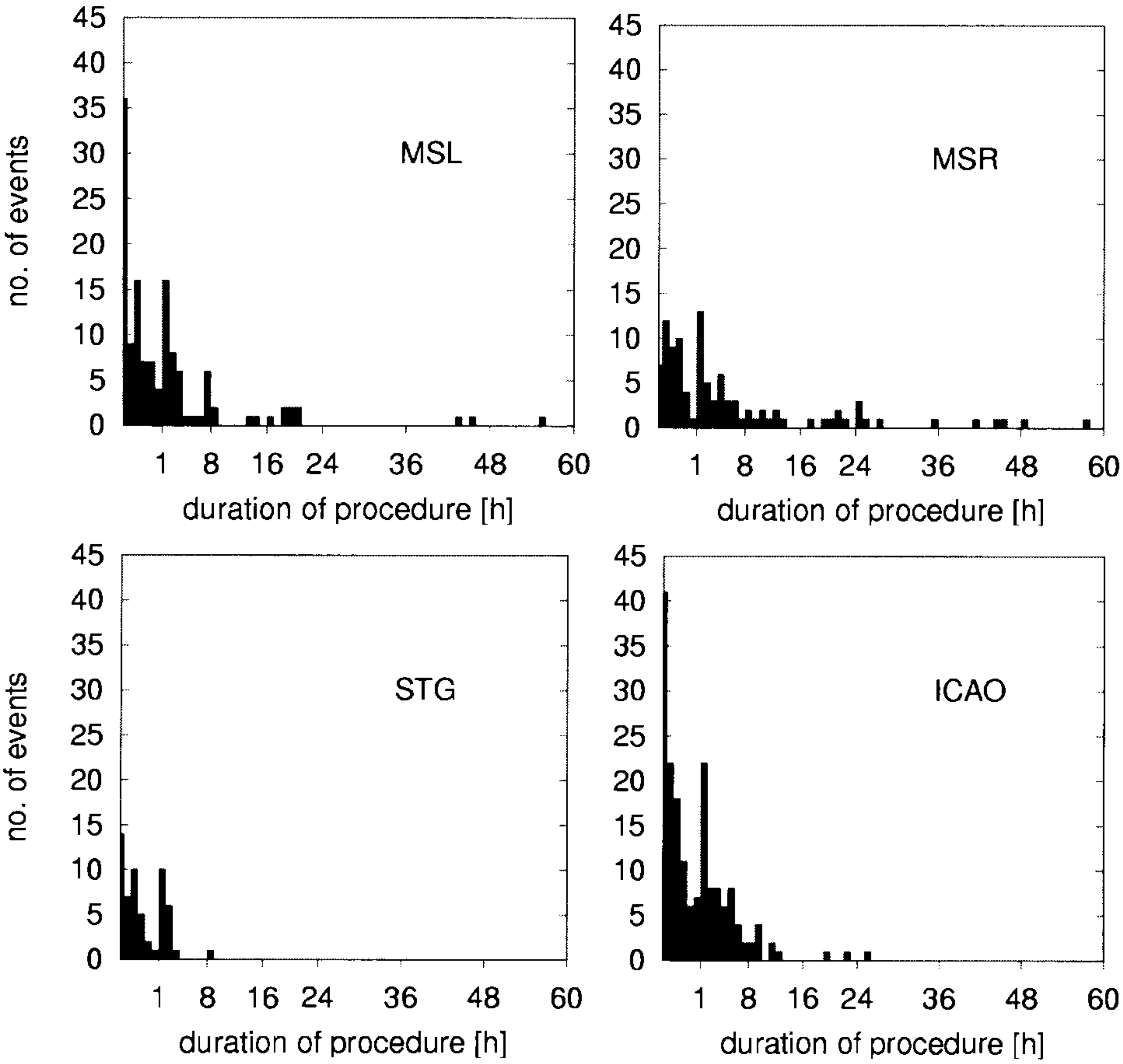



**Figure 14.** Number of events versus duration of potential DFS wake avoidance procedures in hours for HM aircraft pairs; a 10 min interval is used in the 1st hour, the interval is 1 hour afterwards. The median durations of the procedures amount to 40 min for MSL, 90 min for MSR, 30 min for STG and 40 min for ICAO, respectively.

**Table 2. Average Minimum Separation Time and Frequency for HH and HM Aircraft Pairs Landing In-trail (LL, RR) or Across (LR, RL) for the Fraction of Time in which Radar Separation was Suggested**

| Landing procedure | Average MST [s] | Frequency of use [%] |
|---|---|---|
| LL HH | 60.0 | 2.6 |
| LL HM | 61.9 | 1.5 |
| LR HH | 0 | 40.3 |
| LR HM = MSL | 0 | 30.7 |
| RL HH | 0 | 54.3 |
| RL HM = MSR | 0 | 47.9 |
| RR HH | 60.0 | 2.6 |
| RR HM | 61.9 | 1.5 |
| STG HH | 0 | 10.0 |
| STG HM | 0 | 3.6 |
| ICAO | | 25.0 |

The cases where DFS-mode STG could have been used for HH (HM) pairings summed up to 10% (3.6%). For the DFS operation modes, the ICAO separation mode was required in only 25% of the time.

Table 3 displays similar information as Table 2 including the assumption that all separation times between 0 and 100 s (125 s) for HH (HM) pairs could be used. In particular, the use of reduced in-trail separations increases strongly by factors 2.5 (6) although at the expense of larger average MST. The staggered procedures are almost unchanged compared to Table 2 since these values depend predominantly on whether or not a vortex reaches the parallel runway.

The frequencies of use listed in Tables 2 and 3 are predominantly related to wake vortex transport by crosswind. If the predicted vortex descent (or descent and decay) is not used, the periods of ICAO separations increase from 25% to 30.4%, i.e. by 21.6% (or from 25% to 31.9%, i.e. by 27.6%). Accordingly, the frequency of use for "modified staggered" procedures is reduced on average by 9.3% (11.5%). For the procedure "staggered" the reduction amounts to 58% (64%) but this mode is seldom used. A pure crosswind based prediction of lateral transport would cause further reductions in potential benefits. In order to achieve the same level of safety, the uncertainty allowances of such a simple scheme would exceed those of the P2P which incorporates the wake removal mechanisms of lateral transport and effects related to vortex descent and decay.

Questions concerning how long the DFS ConOps MSL, MSR, STG or no one of them (ICAO) separations could be continuously used and how often this happened during the campaign is answered in Figure 14 for pairs of Heavy/Medium aircraft. In the 66 days, the procedures MSL/MSR/STG could have been used 36/7/14 times for only 10 minutes. However, a continuous use of these ConOps for 1 hour would have been possible 16/13/10 times, respectively. Even a usage as long as 8 hours would have been feasible 2/2/1 times, respectively. Somewhat higher numbers hold for the aircraft pairing HH and somewhat

**Table 3. As for Table 2 but all Separation Times Between 0 and 100/125 s are used**

| Landing procedure | Average MST [s] | Frequency of use [%] |
|---|---|---|
| LL HH | 75.7 | 6.6 |
| LL HM | 93.5 | 9.0 |
| LR HH | 0.1 | 40.3 |
| LR HM = MSL | 1.2 | 31.0 |
| RL HH | 0.5 | 54.6 |
| RL HM = MSR | 1.6 | 48.6 |
| RR HH | 75.7 | 6.6 |
| RR HM | 93.5 | 9.0 |

reduced numbers for single runway approaches (not shown). Due to the strong wind conditions in January it would even have been possible to use MSR for HH pairings for one period lasting almost 4 days (93 hours). The median durations of the procedures amount to 40 min for MSL, 90 min for MSR, 30 min for STG and 40 min for ICAO, respectively. Hence, for mode STG, for example, the median number of transitions from STG to another mode is two per hour.

For the interested reader a further analysis reveals which gates impede reduced aircraft separations. This analysis indicated that gate 13 (the one closest to the runway threshold where aircraft fly at 29 m above ground) hinders WSVBS operations for single runway approaches in 51% out of 6042 cases. This is further evidence for the bottleneck close to the ground. Interestingly though, gate 1 (the farthest-out gate at 1077 m height) blocks reduced separations in almost 31% of the cases. This is attributed to the fact that the first approach corridor features the largest dimensions. For staggered and modified staggered approaches, gate 13 is no longer an issue but gate 10 impedes reduced separations 26 to 48% of the time. At this gate two effects appear decisive. First, it is the lowest gate employing numerical cross-wind predictions, which lead to larger uncertainty allowances of vortex position compared with predictions using actual wind measurements. Second, the aircraft vortices are shed at 190 m height where ground effect still contributes to the lateral wake vortex transport for the aircraft parameter combinations with the largest wing spans [Holzäpfel et al., 2009b]. Similar as for the single runway approaches, the first gate with the largest approach corridor dimensions blocks reduced separations for approaches towards the parallel runway system in 10 to 45% of the cases.

Figure 15 shows two examples of traces of the port and starboard vortices of heavy aircraft landing on runway 25R as measured by the LIDAR in the three scan planes shown in Figure 2. For the 18$^{th}$ of January, the WSVBS predicted the modes MSR followed by reduced in-trail separation. The plot, which shows vortex positions of 8 landing heavy aircraft, corroborates both scenarios as the southerly cross-wind prevented the vortices from reaching runway 25L (hence, MSR). The wind became so strong later in the day that a reduced separation in-trail could have been operated. For the 8$^{th}$ of February, WSVBS recommended use of the STG operation followed by MSR. Again, the LIDAR data, now from 32 landing heavy aircraft, confirm the predictions; the wind is very weak and does not transport the vortices to the adjacent runway.

The (manned) LIDAR did not measure continuously throughout the campaign. It was operated on 16 days where it tracked the wake vortices of about 1100 landing heavy aircraft in the three most critical control gates (Figure 2). In all these cases it was found that the recommended

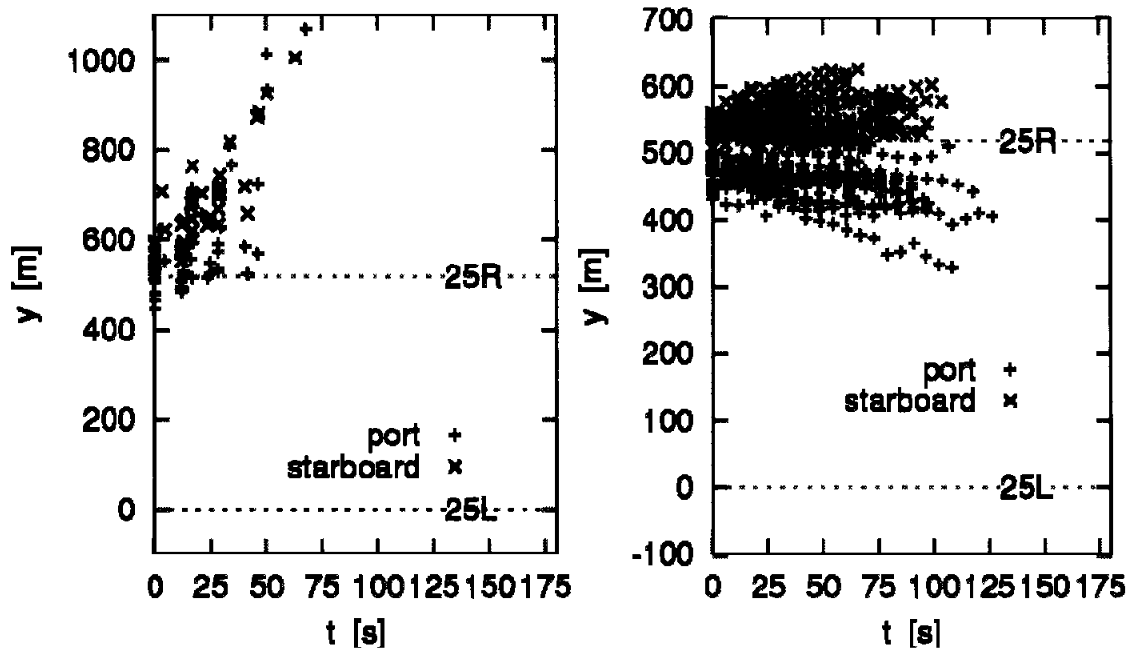



**Figure 15.** Lateral positions of wake vortices vs. vortex age from 8, 32 heavy aircraft landing on 25 R on 18th Jan. (left) and 8th Feb. (right) 2007, respectively, as traced by the LIDAR in the three scan planes.

operation mode was well predicted — no vortices were detected in the flight corridor after the predicted minimum separation time.

## CONCLUSIONS

DLR has developed a wake vortex advisory system for airports and air traffic control, the *Wirbelschleppen-Vorhersage- und -Beobachtungs-system*, named WSVBS. It has the components SODAR, RASS, USA and NOWVIV for monitoring and forecasting the local weather around the airport in Frankfurt (or any other airport). The components P2P and SHAPe are used to predict wake transport and decay and required safety areas. A LIDAR is employed to survey the lower most-critical heights along the glide path for wake vortices. WSVBS is integrated in the arrival manager AMAN of DLR. The WSVBS prediction horizon is larger than 45 min (as required by air traffic controllers) and updates every 10 minutes. It predicts which of the DFS concepts of operation for wake avoidance and associated procedures may be utilized and it further predicts additional temporal separations for in-trail traffic.

The WSVBS demonstrated its functionality at Frankfurt airport during a 66 day evaluation period from 18/12/06 until 28/02/07. It covered the glide paths of runways 25L and R from the final approach fix (11 nmi) to the threshold. It combined measured and forecast meteorological data for wake prediction. From the 66 days of performance testing at Frankfurt we found that [Gerz et al., 2007]:

- the system was stable — no breakdowns of the forecasts occurred,
- aircraft separations could have been reduced 75% of the time compared with ICAO standards,
- reduced separation procedures could have been continuously applied for at least several tens of minutes routinely and up to several hours occasionally,
- the predictions were correct for the 1100 landings observed during 16 days of LIDAR measurement.

We acknowledge that the period of 66 days is rather short to draw final conclusions on the performance of the WSVBS. However, the performance of the system has also been elaborated by using a numerical database (Frech et al., 2007) consisting of one full year of meteorological data along the glide paths of the Frankfurt Airport. These results show similar statistics in the possible use of the operational concepts as reported here from the 66 days field campaign.

Fast-time simulations revealed that the concepts of operation introduced by DFS (i.e. MSL, MSR, STG with 2.5 nmi or 70 s as the minimum separation) and utilized by WSVBS for the Frankfurt Airport, yield significant reductions in delay and/or a 3% increase in capacity, taking into account the real traffic mix and operational constraints. Relaxing the DFS constraints and allowing more operation modes would further increase capacity.

We consider these capacity gains as tactical. “Tactical” means that the system aims at increasing the punctuality of flight operations by minimising holding patterns. After experience has been gained over some years of operation (including diurnal and seasonal statistics of meteorological quantities along the glide path) the system may also allow increasing the number of flight operations at the airport, i.e. gain capacity “strategically” probably depending on the time of the day or the season of the year.

From scientific and technological perspectives, the WSVBS has reached a mature and useful state. However, before the system can be handed over to users to become a customized and fully operational system, further steps are necessary. A risk analysis will be pursued and other field campaigns are planned in the context of forthcoming national and international campaigns, like in DLR’s follow-on project *Weather & Flying* and within the SESAR Joint Undertaking.

## ACKNOWLEDGEMENTS

We highly acknowledge the support and help from the Fraport AG, Frankfurt, in setting up and running the field trial at their airport. We also thank the German Meteorological Service, DWD, in Offenbach, for hosting our Local Operation Centre in their observer house at the airport and supplying the model output data of their routine weather forecasts. The German air traffic safety provider DFS, Langen, is acknowledged for their support. We thank Fa. Metek, Elmshorn, for renting their very reliable and robust meteorological profiler system to us and Dr. Andreas Wiegele for his support in performing and evaluating the LIDAR measurement campaigns. The work presented here was funded by the DLR project *Wirbelschleppe* and did benefit from the EU projects *ATC-Wake* (IST-2001-34729), *FAR-Wake* (FP6–012238), *FLYSAFE* (AIP4-CT-2005-516 167), and the European Thematic Network *WakeNet2-Europe* (G4RT-CT-2002-05115). We finally thank four anonymous reviewers and the editors for their thoughtful comments and suggestions. Special thanks go to one of the reviewers who spared no effort to enhance the manuscripts with high expertise in wording and technical knowledge.

## ACRONYMS

| | |
|---|---|
| AMAN | Arrival Manager |
| ATC | Air Traffic Control |
| ATMOS II | Air Traffic Management and Operations Simulator |
| CSPR | Closely-Spaced Parallel Runways |
| DFS | Deutsche Flugsicherung GmbH |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt |
| DWD | Deutscher Wetterdienst |
| EDR | Eddy Dissipation Rate |
| HH | Heavy aircraft followed by Heavy aircraft |
| HM | Heavy aircraft followed by Medium aircraft |
| ICAO | International Civil Aviation Organization |
| IMC | Instrumented Meteorological Conditions |
| LIDAR | Light Detection and Ranging |
| LM | Lokal Modell |
| LOC | Local Operation Centre |
| MSL | Modified Staggered Left |
| MSR | Modified Staggered Right |
| MST | Minimum Aircraft Separation Time |
| NOWVIV | Nowcasting Wake Vortex Impact Variables |
| MM5 | Mesoscale Meteorology Model 5 |
| P2P | Probabilistic Two-Phase Wake Vortex Model |
| PC | Personal Computer |
| RASS | Radio Acoustic Sounding System |
| SHAPe | Simplified Hazard Area Prediction |
| SIMMOD | discrete-event simulation model |
| SODAR | Sound Detection and Ranging |
| STG | Staggered |
| UMTS | Universal Mobile Telecommunications System |
| USA | Ultra Sonic Anemometer |
| UTC | Universal Time Coordinated |
| WSVBS | Wake Vortex Prediction and Monitoring System |
| WVWS | Wake Vortex Warning System |

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